^{137}Cs, K, Rb and Cs in a *Sphagnum*-dominated peatland in eastern central Sweden

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Abstract. At the open bog ^{137}Cs activity was mainly located in the uppermost 1-4 cm of *Sphagnum* layers whereas at the low pine in deeper (10-12 cm) layers. The migration rate of ^{137}Cs was 0.57 cm yr^{-1} at the open bog site and the migration centre was at a depth of 10.7, while the rate at the low pine site was 0.78 cm yr^{-1} and the migration centre was at 14.9 cm, suggesting an upward transport of caesium in the open bog peat profile. ^{137}Cs was found mainly located within green parts (*Calluna vulgaris*), within roots (*Andromeda polifolia*, *Eriophorum vaginatum* and ***Vaccinium oxycoccos*****) or** showed variable distribution within the plant **(e.g.** *Carex rostrata* and *Menyanthes trifoliata*). Heather and cranberry showed obvious decreases in ^{137}Cs activity concentrations over the 15–18 years since the Chernobyl fallout while activity in other plants remained for the most part unchanged. ^{137}Cs activity concentration and concentrations of K, Rb and Cs concentrations were usually highest in the capitula and/or in the subapical segments and lowest in the lower dead segments. ^{137}Cs activity concentrations in *Sphagnum* well correlated with concentrations of Rb and stable Cs while only weak correlations were found betwen^{137}Cs and K.

1. INTRODUCTION

Peatlands, in particular boreal bogs which located in the northern hemisphere are generally nutrient-poor habitats. Hence bogs are ombrotrophic, i.e., all water and nutrient supply to the vegetation is from aerial dust and precipitation, resulting in an extremely nutrient-poor ecosystem often formed and dominated by peat mosses (*Sphagnum*). *Sphagnum*-dominated peatlands with some groundwater inflow (i.e. weakly minerotrophic 'poor fens') are almost as nutrient poor and acid as true bogs. In Sweden, the area covered by natural or near-natural mires comprises about 4.9 million ha or 11.0% of total land area [1]. *Sphagnum* plants absorb and retain substantial amount of fallout-derived radiocaesium [2].

The transfer of ^{137}Cs within a raised bog ecosystem is different from that in forest and pastures or on agricultural land. Recent studies [4] show that in *Sphagnum* layers, ^{137}Cs is translocated continuously towards to the growing apex of the *Sphagnum* shoots, where it is accumulated.

The chemical behaviour of ^{137}Cs could be expected to be similar to that of stable Cs and other alkali metals, K, Rb, which have rather similar physicochemical properties. Stable Cs usually provides a useful analogy for observing long-term variation and transfer parameters of ^{137}Cs in a specific environment, particularly in peatlands that are cut of from input of Cs from the

mineral soil. However, the relationships between Cs and K are not completely understood, since Cs does not always show high correlations with K and it has been suggested that there is an alternative pathway for Cs uptake into fungal cells [5].

Virtually no studies have been conducted to clarify the influence of alkali metals (Cs, Rb) on ^{137}Cs distribution and cycling processes in nutrient-poor peatlands. Such information is needed to accurately interpret the processes that determine caesium uptake and binding. Plant species growing on peat have - to a varying degree - the capacity to influence uptake and binding of the radionuclides but no systematic study has been carried out involving all the dominant species of *Sphagnum* peatlands and comprehending both competitions for radionuclides and for nutrients. The important role of *Sphagnum* mosses in mineral nutrient turnover in nutrient-poor ecosystems, in particular their role in ^{137}Cs uptake and binding necessitates a clear understanding of the mechanisms involved.

The main aim of the present study was to estimate and compare ^{137}Cs migration and uptake in two different parts of a bog area, an open bog and low pine site and to compare the distribution of ^{137}Cs, K, Rb and Cs in the uppermost capitulum and subapical segments of *Sphagnum* mosses to be able to discuss the possible mechanisms involved in ^{137}Cs uptake and retention within *Sphagnum* plants. We also quantified ^{137}Cs in the dominant vascular plants associated with *Sphagnum* and its distribution within these plants.

2. **MATERIALS AND METHODS**

2.1. Study area

The study area was a small peatland (Pålsjömossen) within a coniferous forest in eastern central Sweden, about 35 km NW of Uppsala (60°03′40″ N, 17°07′47″ E). The peatland can be divided on the basis of the vegetation present into two different parts, open bog and low pine sites. From each of these two sites composite samples of plants were collected in 1989 and again during the period 2004-2007. In 2007-2008 the sampled part of the peatland was open and *Sphagnum*-dominated. The area had scattered hummocks mostly built by *S. fuscum*, and dominated by dwarf-shrubs such as *Andromeda polifolia, Calluna vulgaris*, *Empetrum nigrum* and *Vaccinium oxycoccos*. Sampling was made within a 25-m^2 low, flat “lawn community” [6] with the water table most of the time less than 15 cm below the surface. These parts were totally covered by *S. papillosum*, *S. angustifolium* and *S. magellanicum* with an abundant cover of *Eriophorum vaginatum*. The surface water pH was 3.9-4.4 (June 2009).

2.2. Sampling and treatment

2.2.1. Profiles

Six profiles were analysed in 2005, four at the open bog site and two at the low pine site. Samples were collected by digging with a spade and cutting into 10×10 cm^2 blocks with a saw to a total depth of between 30 and 40 cm. In June

1989, three peat profiles from the open bog site were sampled using a cylindrical steel bore (diameter 57 mm) to a depth of about 20 cm.

2.2.2. Vascular plants

During the period 2004-2005, 27 and 18 composite plant samples were collected from the open bog and low pine site over time from the beginning of May to November. In 2006-2007, 24 plant samples were collected from the open bog and 15 samples from the low pine site during the period May-September. In total, 122 plants (76 from open bog and 46 from low pine) were sampled and analysed. Additionally, 63 composite vascular plant samples were collected from the end of July to the middle of September 2008. The samples were divided into active green tissue, supportive tissue, and roots (in some species fine roots; < 2 mm in diameter). Some species were further divided into finer sections. For *Drosera* the whole plant was analyzed. The samples were carefully cleaned of any extraneous fragments, and dried at 40°C to constant weight. They were then milled to 2 mm or cut into fragments of a few mm to achieve homogeneous and well-mixed samples that were analysed for activity concentration of ^{137}Cs.

2.2.3. Sphagnum mosses

Samples of individual *Sphagnum* shoots that held together down to 20 cm were randomly collected in 2007 (May and September) and 2008 (July, August and September). All together 13 samples of *Sphagnum* plants were collected and analysed; 3 in 2007 and 10 sets in 2008. Each sample consisted of approx. of 20-60 individual *Sphagnum* plants (mostly *S. papillosum*, in a few cases *S. angustifolium* or *S. magellanicum*). In the laboratory fresh individual erect and tightly interwoven *Sphagnum* plants were sectioned into 1 cm (0-10) or 2 cm (10-20 cm) long segments down to 20 cm from the growing apex.

2.2.4. Measurements and data treatment

The activity concentration (Bq kg^{-1}) of ^{137}Cs in plant samples was determined using well-calibrated HPGe detectors. All ^{137}Cs activity concentrations were recalculated to the sampling date and expressed on a dry mass basis. Analysis of *Sphagnum* segments for K, Rb and Cs was done by a combination of ICP-AES and ICP-SFMS techniques by ALS Scandinavia AB. Differences in ^{137}Cs activity concentration among species and among plant parts within species were tested by ANOVA followed by Tukey pairwise comparisons using Minitab ver. 15 (Minitab Inc., 2006).

3. RESULTS

3.1 ^{137}Cs in peat profiles

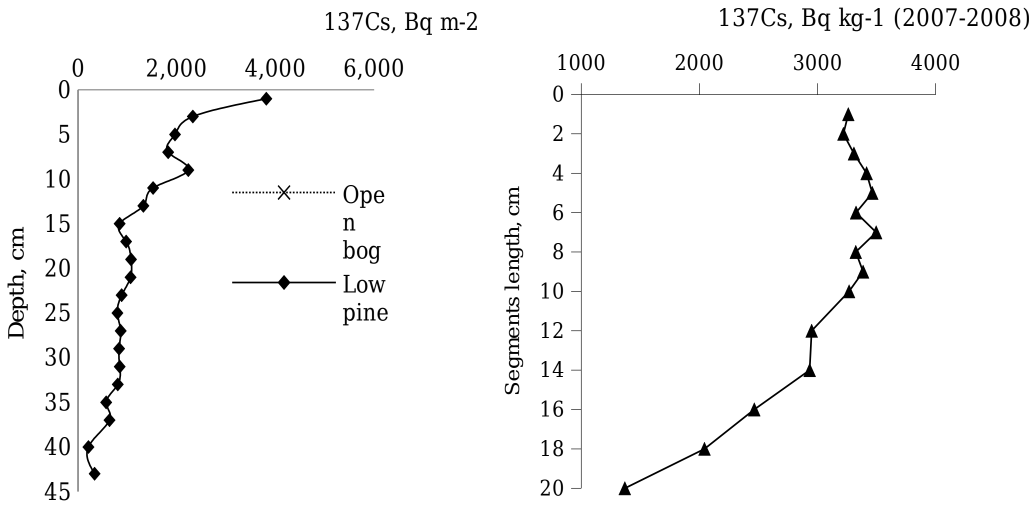
At the open bog site there was a strong retention of ^{137}Cs in the upper 0-2 and 2-6 cm layers with respective values about 6 000 and 3 000 Bq m^{-2} (Figure 1a). At

the low pine site the ^{137}Cs deposition in the upper 0-2 cm layer was 4 000 Bq m^{-2} and decreased to about 2 000 Bq m^{-2} at the depth between 2 and 10 cm. The estimated mean ^{137}Cs deposition was very similar at both sites: 23.0 kBq m^{-2} in the open bog and 23.6 kBq m^{-2} at the low pine site. The migration centre was 10.72 and 14.98 cm and ^{137}Cs migration rate was 0.57 and 0.78 cm y-1 at the open bog and low pine respectively.

Thus, there seemed to be a rather slow vertical migration of ^{137}Cs, indicating binding of this radionuclide by living matter since the clay content in this ecosystem is extremely low or non-existent and there is very little fungal mycelium present. Most of the ^{137}Cs activity in the peat profiles was found in living moss plants, mainly in the apical few cm of the *Sphagnum* mosses, which has formed since the Chernobyl fallout occurred. This indicates that there has been upward migration of ^{137}Cs within the *Sphagnum* plants. According to Gerdol et al. [7] high concentrations of Chernobyl-derived ^{137}Cs in *Sphagnum* segments produced after 1986 are due to continuous translocation of ^{137}Cs towards the apex, probably as a result of the chemical similarity between caesium and potassium.

3.2. ^{137}Cs activity concentration in plants

Within the sixteen-year study period, the mean ^{137}Cs activity in plants on the open bog had decreased by a factor of 2.1 for heather (*C. vulgaris)*, 5.9 for sundew (*D. rotundifolia)* and 6.7 for cranberry (*V. oxycoccus)*. For bog bean (*M. trifoliate)* and cloudberry (*R. chamaemorus)* only a slight decrease in ^{137}Cs activity was observed within the study period (Table 1). At the low pine site ^{137}Cs activity concentration in heather was about 11 200 Bq kg^{-1} in 2004-2007, having decreased from 22 300 Bq kg^{-1} in 1989. In contrast, the activity concentration in cloudberry plants increased slightly during the study period (1989-2007).



a) b)

Figure 1. Vertical ^{137}Cs deposition (Bq m^{-2}) in the peat profile at the open bog and low pine sites (mean values from four profiles collected in 2005) (a); Average ^{137}Cs activity concentration (Bq kg^{-1}) in *Sphagnum* segments (+/- SE, n = 13) (b).

Thus, the ^{137}Cs activity concentration in heather grown on the low pine site was about half that in heather grown on the open bog, while cloudberry plants had a similar concentration at both sites (Table 1). When different plant parts were compared within species (Table 2), the general pattern was that brown, senescent parts had low, and roots had high activity concentration. Statistically significant differences were found in *C. vulgaris* where the activity concentration was higher in the green parts than in the woody parts ($F_{2, 4}$ = 9.35; P = 0.031). The results show a strong tendency of ^{137}Cs being relocated by biological processes within vascular plants into actively growing leaves and fine roots. ^{137}Cs uptake was very high, particularly in some of the plants growing very sparsely on the open bog site.

Table 1. ^{137}Cs activity concentration (Bq kg^{-1}, mean±SE) in plant species growing on the open bog and low pine sites in the present study (2004-2005) and in 1989 (n=no. of samples analysed).

Plant species	Open bog				Low pine			
	2004-2007		1989		2004-2007		1989	
	n	^{137}Cs	n	^{137}Cs	n	^{137}Cs	n	^{137}Cs
Calluna vulgaris	5	20 407±1 668	7	43 493±2 741	5	11 248±1 501	4	22 313±35 7
Drosera rotundifolia	-	4 283	4	25 002±740	-	-	-	-
Menyanthes trifoliate	4	2 782±467	3	2 862±217	-	-	-	-
Rubus chamaemorus	2	3 283±773	3	4 241±1 847	2	4 374±1 644	5	3 015±59 8
Vaccinium oxycoccus	3	2 183±553	3	14 719±3 099	-	861	-	2 946

Table 2. Activity concentration of ^{137}Cs (mean values and range, kBq kg^{-1}) in various plants organs, 2008. Fine roots were defined as < 2 mm in diameter. (n=no. of samples analysed).

Plant species	n	Green shoots	Woody parts	Roots
Andromeda polifolia	3	1.1 (0.85-1.4)	1.0 (0.88-1.3)	3.1 (2.7-4.6)[1]
Calluna vulgaris	3	12.8 (9.3-17.1)	2.1 (2.0-2.1)	5.7 (5.1-6.3)[1]
Carex rostrata	4	4.4 (1.9-10.6)[2]	1.8 (1.2-3.1)[3]	6.2 (1.9-10.6)
Eriophorum vaginatum	4	2.0 (1.3-3.3)	1.8 (1.2-3.4)[3]	7.3 (3.2-11.8)
Menyanthes trifoliata	5	2.6 (2.5-3.0)[4]	1.6 (1.3-2.3)[5]	2.3 (1.6-3.3)
Vaccinium oxycoccos	3	1.5 (1.1-1.7)	1.6 (1.5-1.9)	3.2 (2.2-3.3)[1]

[1] fine roots; 2 green leaves; [3] senescent leaves; [4] shoots and leaves; [5] stems and rhizomes;

3.3. ^{137}Cs activity concentration in *Sphagnum*

In Figure 1b averaged ^{137}Cs activity concentrations in *Sphagnum* segments are presented. Summarized data show that within the upper 10 cm from the capitulum ^{137}Cs activity concentration in *Sphagnum* plants was about 3 350 Bq kg^{-1} with relatively small variations. Below 10-12 cm the activity gradually

declines with depth and in the lowest segments of *Sphagnum* ^{137}Cs activity concentrations was about 1 370 Bq kg^{-1}.

3.4. Potassium, rubidium and caesium concentrations in *Sphagnum*

For individual *Sphagnum* samples potassium concentrations ranged between 508 and 4 970 mg kg^{-1} (mean 3 096); rubidium between 2.4 and 31.4 mg kg^{-1} (mean 18.9) and Cs between 0.046 and 0.363 mg kg^{-1} (mean 0.204). Concentrations of Rb and Cs were rather constant in the upper 0-10 cm segments of *Sphagnum* moss and gradually declined in the lower parts of the plant length, whereas the concentration of K decreased with increasing depth below 5 cm. Such distribution can be interpreted as dependent on the living cells of capitula and living green segments in the upper part of *Sphagnum*. Similar patterns of K distribution within *Sphagnum* plants were reported in other studies [8]. Obviously, ^{137}Cs is taken up and relocated by *Sphagnum* plants in similar ways as stable alkali metals studied, since the ratios between K, Rb, Cs and ^{137}Cs in *Sphagnum* segments were much the same down to about 16 cm and displayed slightly different pattern in lower part of the plant.

There were close positive correlations between K, Rb and Cs concentrations and ^{137}Cs activity concentrations in *Sphagnum* segments (Table 3). Correlation between ^{137}Cs activity concentrations and Rb concentrations was highest ($r = 0.95$; $p < 0.001$) in 10-20 cm length of *Sphagnum* plants, while ^{137}Cs and K showed a weaker correlation when only the upper 0-10 cm part of *Sphagnum* plants were analysed ($r = 0.50$; $p < 0.001$).

Table. 3. Correlation coefficients between K, Rb, Cs and ^{137}Cs concentrations in *Sphagnum* segments 0-10 and 10-20 cm ($P < 0.001$).

	K	Rb	Cs	K	Rb	Cs
	0-10 cm			10-20 cm		
Rb	0.63			0.95		
Cs	0.79	0.80		0.74	0.75	
^{137}Cs	0.50	0.89	0.84	0.85	0.95	0.73

Two important features should be pointed out when discussing distributions of K, Rb, Cs and ^{137}Cs in a *Sphagnum*-dominated peatland. Firstly, this type of peatland is an extremely nutrient-poor, where only a few plant and fungal species, which produce small fruit bodies can grow and no mycorrhiza except ericoid mycorrhiza exists. Secondly, the upper part of the stratigraphy is composed of living *Sphagnum* cells which selectively absorb mineral ions from the surrounding water, and binding of such ions can be at exchange sites outside the cell or inside the cell for Cs, K and Rb.

Presumably, ^{137}Cs is binding within capitula, living green segments and dead brown segments of *Sphagnum* plant. According to Gstoettner and Fisher [9] the uptake of some metals (Cd, Cr, and Zn) in *Sphagnum papillosum* is a passive process since they found that living and dead moss accumulated metal equally. Some of the lower parts of *Sphagnum* plants are still alive and able to create a new shoot [10], however, much of lower stem is dead though still connected to the capitulum. Thus, the decrease of ^{137}Cs activity concentration in plant segments below 10 cm likely indicates a release of the radionuclide from dying-off lower part of *Sphagnum* and internal translocation to the capitulum. The mechanism of ^{137}Cs and alkali metals relocation within *Sphagnum* is most likely the same active translocation as described for metabolites by Rydin and

Clymo [11]. The recently suggested external buoyancy-driven transport [12] could redistribute ^{137}Cs, but since field evidence suggested that buoyancy led to a downward migration of K [13] this mechanism seems unlikely.

4. Conclusions

The estimated mean ^{137}Cs inventory was rather similar on both the open bog and low pine sites, but the migration rate was higher at the low pine site than on the open bog and the migration centre at the low pine site was located in approx. 5 cm deeper in the peat profile. At both sites, ^{137}Cs activity concentration in vascular plants either decreased over the period from 1989 to 2004-2007 or remained unchanged. Rooting depth seems to be one of the main factors affecting ^{137}Cs activity in vascular plants on peatlands. The distribution of ^{137}Cs within *Sphagnum* plants was found to be rather similar to stable K, Rb and Cs: highest in the uppermost 0-10 cm segments of *Sphagnum* and gradually decreased in older parts of plant. The most important mechanism for distribution of ^{137}Cs within *Sphagnum* plants seems to be the internal translocation to active tissue and the apex, which can explain the accumulation in the top layer of the mosses, and which can also explain the accumulation in green parts and fine roots in vascular plants.

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